PERFORMANCE ANALYSIS AND COMPARISON OF CLUSTERED AND LINEARLY DISPERSED OPTICAL DEEP SPACE NETWORK

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ABSTRACT

The objective of this paper is to compare the operational and performance cost factors for an Optical Deep Space Network (ODSN). Two major baseline architectures, namely the Linearly Dispersed Optical Subnet (LDOS) and Clustered Optical Subnet (COS), have previously been compared from various perspectives, in the Ground Based Advanced Technology Study (GBATS) and summarized in a report in 1994. Since then, new advances in telescope technology have occurred and new requirements for deep space missions have been proposed. This paper addresses and identifies the need of an update of the findings of GBATS for an ODSN considering the new set of requirements of future deep space missions and the importance to introduce the design to cost consideration during the design of the ODSN itself. The potentials of hybrid architectures and optical arrays for future Deep Space Network are also discussed.

1 INTRODUCTION

In the last decade, NASA/JPL actively considered to explore alternative architectures to Deep Space Relay Satellite System (DSRSS) in order to provide a significant increase in telemetry data return rate from deep space. Among those architectures, one of particular interest was based on free space optical communications because it may offer orders of magnitude increase in transmission bandwidth with a reduction of spacecraft size and weight. Issues concerning the use of optical communications and architectural solutions for an Optical Deep Space Network (ODSN) where presented in the Ground Based Advanced Technology Study (GBATS) [1]. As one of the main findings of the GBATS, two possible network architectures were suggested in order to allow global coverage of the Earth: the Linearly Dispersed Optical Subnet (LDOS) and the Clustered Optical Subnet (COS), Fig. 1. In LDOS, a number of stations (telescopes) are distributed (at equal distance) around the globe in the proximity of the equator. Particularly the GBATS considered the case of six telescopes spaced by 60 degrees. Alternatively, the COS solution consists of a number of cluster networks with each cluster composed of a number of telescopes. In this case the GBATS considered the example of three clusters approximately 120 degrees apart located in the same geographical area as the current Deep Space Network, with each cluster composed of three telescopes (for a total of nine telescopes).

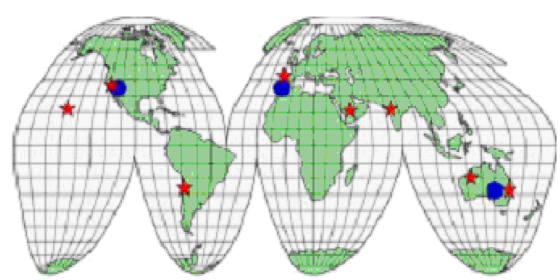

Figure 1. Example of LDOS (star) and COS (circle) architectures for optical deep space network (ODSN).

The selection of the number of stations and their site locations, in both architectures, were driven, among other different factors, by necessity to overcome impediment to the closure of a ground to space link due to the presence of opaque clouds. GBATS indicated that cloud absorption may limit the availability of a single station to less than 70% per individual ground station, therefore the proposed solution was to have telescopes (neighboring telescopes for LDOS or telescopes within the same COS cluster) located in regions having statistically uncorrelated (hopefully anti-correlated) weather patterns operating in space diversity [2].

Since the time GBATS was conducted (1994), several new factors have come into play impacting the costs and performances of telescopes for optical communications. Moreover, mission requirements for deep space have changed. Therefore, the objective of this paper is to present and compare some of the new factors and advances that may impact LDOS and COS architectures. The overall organization of this paper is the following one. Section 2 presents the key changes in technology trends and new requirements that may impact LDOS and COS design. Then, Section 3 discusses the different impact in cost between the two architectures. The paper ends with Section 4 presenting a discussion with final remarks.

2 CHANGES SINCE GBATS

2.1 Technology Trends

As described in the GBATS, both LDOS and COS architecture were based on the deployment over the Earth of a number of telescopes each having 10m of aperture. Due to inherent technology challenges, at the time of the release of the GBATS (1994) there were not built yet 10m telescopes, although some were under construction (e.g., Hobby-Eberly Telescope or HET, and Keck). In the last ten years, new advances in mirror technology (*e.g*., adaptive optics, aberration correction methods, optical phase shifting, wave front sensors, segment edge sensors, and miniature mirror actuators) have been devised to further improve individual telescope performances while still lowering the manufacturing cost [3]. In terms of optical signal detection, more sensitive optical detectors have become available including the development of detector arrays that allows other flexibility in pointing mechanism when combining communication and tracking signal path [4]. Moreover, as a result of global observations via imaging satellites and intensive computations, accurate weather databases have been compiled. Accurate weather predictions, based on the use of such weather databases [2], are of great importance during network operation in helping to program station activities, especially in case of (predicted) cloudy weather with shorter lead times that helps providing smoother handover situations. Cloud coverage statistics extracted from the weather database helps also in the identification of optimal site with better visibility and atmospheric channel availability that can be potential locations for the installation of telescopes belonging to LDOS or COS architectures.

2.2 High Level Requirements

Generally speaking, there are two main factors to consider in the design of a global optical communications network for deep space applications: telescope size (*i.e*., aperture size) and the distance between stations. The size of the individual telescope aperture needs to be selected based on mission needs (*e.g.*, data rate and Earth-to-Spacecraft range). On the other hand, because of weather effects and Earth rotation, a number of telescopes have to be placed within certain distances in order to achieve a global coverage. The distance between the adjacent telescopes is driven by other secondary factors, which are basically derived requirements from 1) outage tolerations, 2) continuity in data stream, 3) operational cost, and 4) minimal requirements on the spacecraft. However, it is important to notice that geopolitical barriers and scarcity of high altitude peaks (for better visibility and high atmospheric transmission) in certain regions of Earth may cause difficulties in the selection of the telescope sites in a global network.

According to the GBATS, the approach to the design of LDOS and COS was based on JPL estimate of Ka Band capability of a 70m antenna. This resulted in a baseline, which was the telemetry performance from Neptune, averaged over a 24-hour period at 240Kbps. In a subsequent JPL study in 1994 [5] a set of 29 different deep space missions characterizing future activities were considered for optical communication links using ground telescope aperture of 10m. These missions were of different types (e.g. flyby, orbiter, lander, probe, etc.) with varying distances and bit rates (specific emphasis was given to 1 Mbps data return from Mars). Similarly to the GBATS, it was concluded that a 10m aperture ground telescope could meet all the mission data rate requirements.

However, requirements indicated in the GBATS and in Ref. [5] need to be revisited considering today's new standards especially if compared to the new Ka-Band baseline of the Deep Space Network (DSN). For instance, GBATS considered a network availability of 90% while Ka-Band baseline for the DSN has been shifted today to 95%. Therefore a further increase of 5% in availability time would drive to different factors in the design of LDOS and COS network, among these one is the increase in the number of required stations. Moreover, a further increase of number of stations can be also caused by the fact that today's requirement for telescope elevation is 20 degrees in spite of the 15 degrees indicated in GBATS. The minimum Sun-Earth-Probe (SEP) angle is another critical parameter to be considered during a space to ground link. For optical communications, as the SEP decreases, the amount of background radiation from the Sun due to sky background and stray light increases many folds. Background radiation worsens the station performances due to an increase of receiver noise. Initially, in the GBATS a minimum 10 degrees of SEP angle was considered. However, according to today's requirements, the outage time of a mission caused by 10 degrees of SEP limit is too large, and therefore the minimum SEP was lowered to 5 degrees instead. However, the lowering SEP minimum angle implies the condition of having telescopes at higher altitudes because likely the aerosol distribution is lower at higher altitudes so the related sky background radiance would be reduced as well. In turn, the scarcity of available high peaks imparts a reduction in the choice of possible locations available for housing telescopes with an increase of cost if more remote locations need to be considered. Finally, the impact of cost associated with a large aperture of 10m on the global network is still high and other alternatives may be necessary to evaluate.

2.2.1 ODSN Mission Needs

The GBATS considered missions consisting of a single stand-alone spacecraft in deep space. A special emphasis was given to a Mars mission as the baseline to derive the operation concepts. However, a new set of typical missions representing the optical link scenarios of future ODSN need to be defined, i.e. a mission suite. This must include formation flying (i.e., cluster of spacecraft) with capabilities of orbital management of the cluster, and it must take into account the possible increase in uplink data rates for ground to deep space communications and the use of techniques of laser ranging and inter-satellite tracking. Of course, a mission suite is greatly dependent on the link geometry in an optical communication scenario, which suggests that operational concepts of a future ODSN need to be studied with great care. In fact, existing operational concepts of the JPL/NASA Deep Space Network (DSN) need to be readapted for an ODSN.

2.3 New Candidate Architectures

Other major factors that impact today's consideration of LDOS and COS are a number of alternative global network architectures that have been considered more recently, namely the optical arrays, RF arrays, and hybrids. These architectures are discussed next.

2.3.1 Optical arrays

Although the GABTS baseline for an ODSN was based on 10m-aperture ground telescopes, it was not specified how many of these stations were necessary to guarantee Earth coverage in order to meet high level requirements. This discussion, therefore, was somehow left open. For instance, it was concluded that COS architectures would require 12m-15m aperture telescopes (instead of 10m) to make up for the difference of 1.5dB-5dB in performance that space-based telescopes [1] may offer. However, the cost of a telescope increases exponentially with the optic diameter (see Section 3), and an aperture size increase to 12m-15m from 10m may correspond to a relative increase in cost by at least 44% to 125% respectively. Moreover, for larger diameter telescopes, other cost factors must be taken into account as viable solutions to compensate for gravitational effects over the main reflector as well as environmental restrictions.

In the last few years, it has been envisioned, as a solution to problems (and higher costs) arising from the deployment of larger telescopes, to consider arrays of smaller sized telescopes, *e.g.*, 5m-8m. Currently, there are several different designs proposed to synthesize a larger aperture from an aggregation of smaller sized telescopes for astronomical applications [6,7].

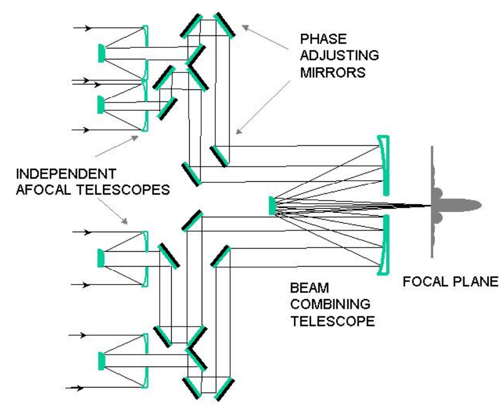

Fig. 2 Telescope Array Configuration

Figure 2 shows one example of combining the signals received by each individual smaller telescope to synthesize a larger aperture. Until now, phased array telescopes have been developed for astronomy, further investigations are therefore needed to understand how this technology can be adopted for optical communication telescopes as such required in the ODSN. In fact, for optical communication applications the instrument and operation cost of optical arrays may very well be compensated by cut back in costs associated with surface figure, environment effects, and facilities. Considering the GBATS requirements, four identical 5m telescopes may be used to synthesize a 10m aperture, with a gain of lower cost. From an operational point of view, another additional advantage offered by an optical array is its flexibility in resource allocations. For example, each individual telescope may be used separately when allocating telescope resources to various types of mission needs such as the support of simultaneous multiple missions each requiring a lower data rate.

2.3.2 RF arrays of small 12m reflectors

In October 2001, in response to NASA's strategic plan for 10-100 times higher receiver sensitivity JPL started its RF array initiative. Inspired by astronomical observations, the RF array aperture study targeted to achieve a resolution of 100 micro arcsec or better. Such a resolution is infeasible to obtain with a single large aperture due to background noise, which is the dominant noise component for receiver sensitivity below 10 GHz. The key requirement that drives the design of RF array of reflectors (*e.g.*, 12m) is the spatial resolution, which in turn depends on the longest baseline (*i.e.*, largest dimension of the array). Specific features of the RF array are its multi-beam capability, flexibility in scheduling, and graceful degradation of the Gain/System Temperature (G/T) of the array. A major drawback of the RF array of reflector antennas is that it lacks the uplink capability in its current design. RF array facility cost is dominated by the large lot area necessary for the array deployment, which is required to accommodate for the large number of reflectors per site. Specifically, hundreds of 12m antennas need to be spread over a large area with approximately 60m separations from each other. Until now, no study has been made in comparing a global optical communications network with that of a global RF array network, since both architecture studies are still in their early stages. However, the lot area required for facility, the achievable data rate per unit land (Mbps/km^2), the operational complexity (*e.g.*, number of required personnel for operation), the maintenance and the life cycle cost are among the cost figures that should be considered when comparing the RF array of reflector antennas with the ODSN.

2.3.3 Hybrid architectures

All the architectures so far discussed may present interesting innovations and some drawbacks as well when considered for a global network. Therefore, one may think that using hybrid solutions it is possible to optimize the performance of a future Deep Space Network. While a detailed analysis and comparison of hybrid architectures is beyond the scope of this paper, some highlights could help setting groundwork for an early study of hybrid concepts. Hybrid architectures could be categorized as **1)** LDOS & COS; **2)** Optical/RF.

To understand the concept of LDOS & COS hybrid, one can start with a generic ODSN architecture that may resemble generally to an LDOS. However, it may be possible that some of the site locations on the LDOS can have statistical cloud coverage not able to guarantee the requirements for channel availability. In this case, a single (or more) telescope can be substituted by a telescope cluster as in a COS, de facto creating a hybrid LDOS & COS. Clearly, hybridizing LDOS and COS does not help lowering the network cost (*i.e.*, it requires more telescopes) while it definitely improves the overall performance since the two architectures complement each other (*i.e.*, better line of sight coverage of LDOS combined with better weather availability of COS). Another possible alternative for hybrid architecture is the Optical/RF concept eventually integrated with future Internet satellite systems [8]. This concept is better visualized in Fig. 3. Here, an orbiting network of optical telescopes receives a telemetry signal from deep space and transfer it via optical crosslink to future Internet satellite systems around Earth, which can perform the operations of data delivery and distribution via Ka-band RF link to Earth. Note the versatility of this architecture. The orbiting telescope can act as an ideal receiver with no restrictions by the atmospheric channel, while the Internet satellite network is a perfect tool for data distribution because it inherently may provide capabilities for data handling, weather diversity, and global coverage. The cost of this last hybrid solution is not clear. Indeed the main uncertainty is derived by the cost evaluation of the orbiting network of telescopes, on the other hand prospected cost reduction in the data delivery operated by the Internet satellite network makes worthy of evaluation the Optical/RF hybrid concept.

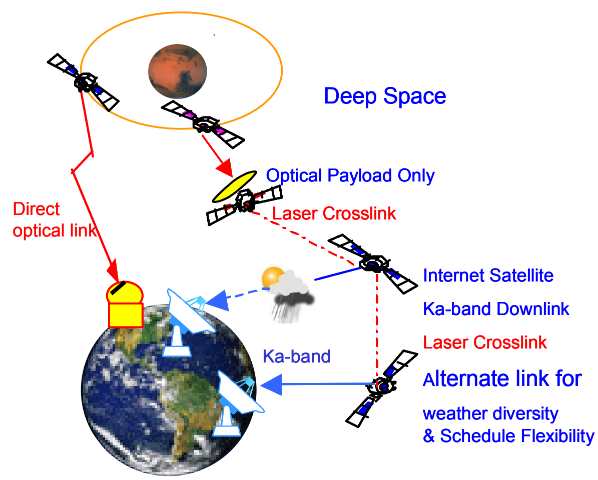

Fig. 3 Hybrid architecture for RF/Optic ODSN

3 COST ESTIMATING METHODS

A few astronomical 10m telescopes have already been designed and built so far (*e.g.*, Keck and HET), however, currently there does not exist a 10m telescope for optical communications for deep space applications. Therefore, detailed cost estimation models for large telescopes for optical communications are not yet available. However, in the rest of this section we present some of the lessons learned from the construction of the astronomical telescopes so that we may apply these lessons to future large aperture optical communications telescopes.

3.1 Scale laws & predictions

A cost-performance model was introduced by Lesh *et al.* in Ref. [9] where it was presented a relation of cost versus aperture size, and mirror surface quality for large telescopes. According to Ref. [9,10], telescope cost increases exponentially with the aperture diameter (D^{β}) with a factor β = 2.4 -2.8. A similar relationship for the aperture cost was also presented later in literature [10]. On the other hand, primary mirror surface is another factor that increases the telescope cost exponentially. Indeed it is true that optical communication does not require per se a great quality primary mirror (termed in Literature as a 'photon bucket'), but it is also true that narrower field of view can be of great importance to reduce sun background radiance and improved tracking accuracy. Clearly, this is an argument open to debate in the near future.

Ref. [9] also indicates that the 10m telescope size falls right at the knee of the cost curve versus communication growth. This finding implies that the 12m-15m aperture sizes, which were recommended by GBATS report for LDOS and COS are on the steep side of the cost curve. At the same time, one must note that the telescope price scale has greatly changed in time. As an example, the 10m Keck-I in 1992 cost was 100M (270 tons), the Mayall 4m telescope at Kitt Peak in 1973 was 10.6 M (350 tons). Therefore, after correction for inflation, the Keck-I should have cost 400 M if there have not been technological breakthroughs [10].

3.2 Design to Cost

The GBATS evaluated the cost for one example of LDOS composed of 6 stations. The cost estimation was primarily based on expert opinion, which is the fastest approach, although a biased one, to cost estimates. Another approach for cost estimation is termed parametric approach. The parametric approach is based on historical data and it has the final purpose to link all the different cost factors of a desired telescope (*i.e.* aperture size, data return rate, receiver subsystem, etc.) with a parametric relationship. Once obtained the parametric relationship, final cost can be easily controlled, tuned and predicted by changing the different cost factors. However, this last approach has the following drawbacks: **1)** it may be difficult to generate for architectures of different natures; **2)** errors in historical data can cause large cost errors; **3)** it does not take into account changes over time for the different cost factors. Unfortunately, a large set of historical data for large aperture telescope is not yet available up to date, which makes it difficult to use a parametric approach for design to cost of an ODSN. As a solution, the ODSN study group at JPL in order to update GBATS cost estimation for today's scenario is using a design heritage approach. Such an approach is more simply based on experience learned in the recent deployment of large aperture telescopes such as HET. Results of this investigation are being applied to the design of ODSN, which will be presented in a near future in Literature.

Since the life cycle cost (see section 3.4) of the telescope network is the dominating factor over the long term, a good cost design scheme is one that targets the minimization of the life cycle cost (LCC) as well. This concept is referred to as design to cost (DTC). GBATS considered the life cycle cost of LDOS and COS, but did not incorporate it early in the design strategy. Instead, a DTC approach must be considered in early conceptual formation of the architecture. In fact, over 60% [10] of the life cycle cost is determined by decisions made before the conceptual design phase. Therefore, a successful cost estimation for the ODSN will include a design heritage analogy merged with DTC at the inception of the design of the global network.

3. 3 Figures of Merits

Ref [10] illustrates how the DTC approach can best be utilized at the early stages of the conceptual design. Specifically, the emphasis of the design should be put on the primary functions of the network. Also, alternative designs of the primary functions of the network must be considered before a specific architecture is selected for further detailed studies. As a lesson learned from Hobby-Eberly Telescope design, 75% of the design had to be changed when the implementation phase started in order to meet the cost objectives. In short, GBATS did not use any specific figures of merits and had no definition of a cost function. Multiple design options need to be considered at early stages and down selected based on figures of merit. Obviously, a good cost function is one that emphasizes the primary functions required by the customer (*i.e.*, optical mission suite). Finally, in order to minimize the life cycle cost at the early stages of the design, the figures of merit shall put emphasis on simple operational modes.

3. 4 Life Cycle Cost (LCC)

The selection of architecture for the ODSN is affected by considerations of operations and maintenance costs as well as performances. Often this combination of considerations is handled through LCC analysis. However, it is important to notice that the cost considerations for new capabilities are much more sensitive to the availability of implementation funds and the time profile of the funding itself, than they are to the LCC. Therefore, in case of funding uncertainty, the primary use of LCC analysis is to guide the design and development work.

Since ODSN lacks to date a complete defined set of requirements, a LCC design is not currently applicable, however, a good start for the ODSN LCC design is to learn from the experience with the current NASA/JPL Deep Space Network (DSN). The current 70m antenna at Goldstone started life as a 64m antenna and was expanded to 70m in the 1980's. The antenna was designed for 10 years, but is still in operation 36 years later with prospects of 10, 15 or even 25-year life extensions. Therefore, the major assets of the ODSN (such as the telescope) should be designed for an operational lifetime in excess of 25 years and maybe for as long as 50 years.

During conceptual design of a network, special emphasis must be put on the minimization of the maintenance cost. In fact, if different designs are possible, the design choice is the one that guarantees lowest operation and maintenance cost, while maintaining approximately the same implementation cost. As an example, for astronomical telescopes, 3%-6% (per year) of the construction cost has been reported to be the cost estimate for the telescope operation (observation) [10] while an additional 3%-5% (per year) has been reported for maintenance and upgrades. Therefore, over its lifetime, the cumulative operation and maintenance cost of the individual telescope can be well over double the construction cost.

Generally from the operations viewpoint it is highly desirable to deploy a system that functions largely unattended. In this case it is likely that the telescopes (preferably located on high mountain tops) and the data-processing/control centers (preferably located near urban centers) will not be in the same physical locations. Therefore robust autonomous operation of the telescope is a must. Logistically, the COS has an advantage because the apertures of the same cluster (*e.g.*, 3 apertures per cluster) are still in the same general area, even though each cluster is in a different region because of the need of weather diversity.

Except for software related activities, the station maintenance is not feasible from a remote control center. Therefore, all parts of an ODSN installation need to be accessible within a reasonable distance (*e.g.*, 30 to 60 minute drive) from the control/logistic facility. Note that an increase of the travel time lowers overall the availability of the personnel and safety requirements mandate the presence of at least two people for any work (routine or repair) at the telescope site.

3.5 Site Selection & Facility Impact

Sites selected for the ODSN need to meet most, if not all, of the following conditions **1)** latitude in proximity of the equator (with +/-40 degrees maximum); **2)** longitude according to the architecture requirements (see Fig. 1); **3)** elevation higher than 1km (preferably higher) for high atmospheric transmission and low sky radiance; **4)** low cloud coverage with fairly constant and predictable weather; **5)** Sites must have a minimum mutual view period of 4 hours with at least one other site; **6)** absence of geopolitical issues for site locations outside the United States.

Additionally, the sites should be close enough to population centers to afford the amenities needed to attract operators.

3.5.1 Facility Impacts on Cost

Beside the cost of actual scientific instrumentations (hardware and software) of a telescope, great care must be put in considering the impact of facility design and implementation on total cost.

The functional requirements for the ODSN facilities fall into five major categories: **1)** shelter and storage, **2)** utilities (water, waste, power/fuel, and communications), **3)** protection and safety, **4)** environmental control, and **5)** access. Because of the nature of the ODSN it is highly likely that any site will be remote, at a high elevation, and possibly under some form of environmental protection, which implies that the final complex will be self-contained and self-sufficient. Of course, it must be considered that the facilities required during the construction phase will differ from those needed during the operational phase.

During construction, access between the telescope site and the outside world will be paramount. An easy and functional access needs to support the transport of materials (often large and heavy), construction tools (heavy machinery, cranes and welding equipment), and raw materials (to be processed on site), workforce and, communication. Depending on the remoteness of the site, temporary shelter and other human support facilities will be needed for the construction phase.

The cost of access is driven by distance from an existing site that supports material delivery (*e.g.*, a rail head), the terrain, the geology, and the need to protect and restore the environment. The cost of access may also be affected by other political factors such as, requirements for using local workers and firms, licenses and permits.

During the operational phase utilities and particularly the expendables become the major consideration. For self-contained sites, water and fuel must be stored for the re-supply period (currently 2 weeks). Considerations of emergency conditions where access is unavailable (storms, snow, etc.) a 100% safety factor is not unreasonable. Climate conditions at the selected sites need to be assessed to refine this figure.

4 SUMMARY AND CONCLUSION

Historically, the GBATS report was the first attempt to describe possible architectures for the ODSN. However, a number of factors need to be reconsidered since the GBATS for an up-to-date evaluation of architecture design of an optical Deep Space Network. In this paper we emphasized on the need to define a clear set of optical mission suite to derive the new requirements, and figures of merit to test performance of ODSN architectures and alternative designs of future DSN. Particularly for optical communications, link geometry must be evaluated with more emphasis than in the past. In fact link geometry not only drives the possible handoff schedule between adjacent (or not adjacent) telescopes, but it addresses a number of constraints on the possible regions that can house one (or more) telescope. Requirements of high elevation peaks (for low background sky brightness and high atmospheric transmission) and cloud coverage along with geopolitical issues further limit locations for telescopes in a global network. It could be possible, that after a careful consideration for telescope site locations over the globe, the availability of such sites (and their distribution over the globe) can provide a first assessment of feasibility between LDOS and COS. As earlier said, a 10m aperture telescope could be considered as a baseline for the ODSN. However, as also evidenced in the GBATS, the size of the aperture of a telescope of the ODSN is not clearly defined. Intuitively, larger aperture sizes could offer better performances despite their higher cost. However, only after a clear evaluation of performances for the optical mission suite a better indication of the aperture size can be identified.

Because the ODSN design is at its early stages, DTC analysis must be also introduced for the design of the network. Results from the DTC analysis can provide another assessment that can guide towards the selection of one architecture (*e.g.*, LDOS, COS) versus the other. Alternatively, it is also necessary to compare LDOS and COS to hybrid architectures especially with the prospect of evaluating the advances and trends in the technological scenarios for DSN. The ODSN study group at JPL is currently investigating the above-mentioned aspects of the ODSN.

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